The APEX Experiment; a dark matter search at Jefferson Lab Hall A

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APEX Spokespeople

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PostDocs

- Ethan Cline (Stony Brook University, J. Bernauer) work on Optics
- Oliver Jevons data analysis

Simple dark sector model: only introduces a single gauge boson.

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \frac{\epsilon}{2} F^{\mathbf{Y},\mu\nu} F'_{\mu\nu} + F'^{\mu\nu} F'_{\mu\nu} + m_{A'}^2 A'^{\mu} A'_{\mu}$$

This adds to the Standard Model Lagrangian, \mathcal{L}_{SM} :

- A term analogous to the SM electromagnetic force.
- A term analogous to the massive weak bosons in the SM.
- A kinematic mixing term, which combines terms from the Standard Model and new dark sector.

Kinematic mixing

Kinematic mixing parameter, $\epsilon^2 = \frac{\alpha'}{\alpha_{EM}}$, is one of the parameters measured by experiments.

Kinematic mixing refers to interactions crossing between the Standard Model and dark sector.



(Visible Dark Photons)

The new gauge boson (A') serves as a mediator of a 'hidden sector' which can kinematically mix with the SM photon.

• Holdom, Phys. Lett. B 166, 1986

Depending on the mass and lifetimes of the A' and its potential dark matter companions, χ , DM searches at colliders can look for

- a displaced vertex
- missing mass in the final state
- a bump in the background invariant mass spectrum

All of these are used by experiments past, current and future.

• APEX is a bump hunt.

Current status from published results



APEX proposed coverage



- APEX used a 2.138 GeV electron beam incident on a tungsten target (10 foils for a total thickness of 0.028 $X_0 \approx 0.1$ mm).
- Invariant mass reconstructed from coincidence hits in two-arm High Resolution Spectrometer (HRS): e^- in LHRS and e^+ in RHRS.

Each spectrometer was set to a central scattering angle of 5°, with an in-plane angular resolution of \sim 0.6 mrad (\sim 1 MeV invariant mass resolution).



Using standard HRS detector stack in both arms.

- 2 planes of scintillators, for timing
- VDC's, for tracking
- calorimeters and Cherenkov detectors, for PID

Kinematic coverage



Electron momentum vs positron momentum for simulated A' signal events (red crosses) and Bethe-Heitler background events (black crosses) for a beam energy of 3 GeV. The blue box represents spectrometer acceptance that optimises signal-to-background ratio.

Invariant mass spectrum

APEX reconstructed invariant mass of e^+e^- pairs, hitting the HRS arms in coincidence.

In 2010, a test run was taken for APEX, which recorded ${\sim}7.7 {\times}10^5$ candidate events; the full 2019 run recorded ${\sim}5.6 {\times}10^7~e^+e^-$ pairs.

Blinded sample of full data set (10%) used to fix the analysis procedure.

Once agreed upon, the data will be unblinded for the final analysis.



- **Discovery**: scan through final invariant mass spectrum and search for statistically significant peak (taking into account Look Elsewhere Effect).
 - Standard 5σ for discovery.
- Limit Setting: set upper limits for number of signal events throughout mass spectrum, convert to limit in ϵ^2 .
- Fitting potential peak as Gaussian, over background (which can be modelled in different ways).

APEX Peak Search: Discovery

- Wilks' theorem: under null hypothesis the log-likelihood ratio, $t = -2 \ln(\lambda)$, approaches the χ^2 distribution with degrees of freedom equal to parameters of interest $(H_1 - H_0)$
- Define test statistic, \tilde{q}_{μ} , for discovery (with null hypothesis: $\mu = 0 \implies \tilde{q}_0$)

$$egin{aligned} \lambda(\mu=0)&=rac{L(\mu=0,\hat{B},\hat{a}_i)}{L(\hat{\mu},\hat{B},\hat{a}_i)}\ p_\mu&=\int_{ ilde{q}_\mu,obs}^\infty f(ilde{q}_\mu|\mu)d ilde{q}_\mu\ ilde{q}_0&=egin{cases}{-2\ln(\lambda(0))}&\hat{\mu}>0\ +2\ln(\lambda(0))&\hat{\mu}\leq0 \end{aligned}$$



- Start with value of μ at each m and iterate potential μ' until C.L. (Confidence Level) derived from λ reaches pre-set level (0.05) (similar to p-level test) →μ_{up}
- Define 'median limit' as the median value of the signal upper limits from pseudo-experiments (used in 2010 analysis, only used as reference for current search)

 $ightarrow \mu_{\it median}$

APEX Peak Search: Translating to reach

- Translate Confidence Levels for number of signal events at different $m_{A'}$ s into limits on α'/α
- Cross section from proposal of A' production to radiative trident cross section

$$\frac{d\sigma(A')}{d\sigma(\gamma^*)} = \left(\frac{3\pi\epsilon^2}{2N_{eff}\alpha}\right)\frac{m_{A'}}{\delta m}$$

• Using the radiative fraction, *f*, to scale to full trident cross section, we can derive:

$$\epsilon^{2} = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{max} = \frac{1}{f} \frac{\mu_{up}}{(B/\delta m)} \frac{2N_{eff}\alpha}{3\pi m_{A'}}$$

Primary backgrounds to the A' decay process include:

- Real e⁺e⁻ photoproduction
- Radiative trident events
- Bethe-Heitler tridents



The radiative fraction, f, is the ratio of radiative trident events to the total background (as a function of invariant mass).

To calculate f, the following are used:

- cross-sections of each background process (calculated in MadGraph5).
- \bullet simulations of the e^- and γ flux from the 10 target foils, generated using Geant4.

The calculated values of f are fitted with a 1st order polynomial; this function is used to calculate ϵ^2 for each of the tested mass hypotheses.



Analysis performed on blinded data set; shows no significant signal.



Analysis performed on blinded data set; looking at upper limits on signal counts, and 1 and 2σ confidence intervals.



Analysis performed on blinded data set; looking at sensitivity covered by data.





- Systematic studies; inc. invariant mass resolution and choice of background function.
- Recovery of statistics from low efficiency runs.
- Run full peak search on unblinded 2019 data set.

Thank you for listening! Any questions?



BACK UP SLIDES

Consider that the dark photon, A', has mass $m_{A'}$, and that the dark particles involved in kinematic mixing have mass m_{χ} .

- If $2m_e < m_{A'} < 2m_{\chi}$, and the A' lifetime is small, use a bump hunt.
- If $2m_e < m_{A'} < 2m_{\chi}$, and the A' lifetime is non-negligible, search for a displaced vertex.
- If $m_{A'} > 2m_{\chi}$, or the A' lifetime is very large, look for missing mass.

CEBAF at JLab

The Continuous Electron Beam Accelerator Facility at JLab.

- Continuous wave, 12 GeV electron beam
- Polarisable
- Delivers to 4 experimental halls, simultaneously



By default, the Hall A HRS pair has a minimum opening angle of 25°.

A' production is focused at small angles; APEX employed a septum magnet to reach a central angle of 5° for each HRS arm.

APEX therefore requires a way to reconstruct the tracks in the HRS arms that is fine-tuned to this non-standard setup.

APEX set-up; angular reconstruction

Sieve slits are placed in front of the septum. The reconstruction of the slit patterns off calibration targets can then be applied to data in the main run.



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- Scan mass range testing different mass hypothesis with fixed mass range window centred at new mass hypothesis, $m_{A'}$
- Form Profile Likelihood Ratio (PLR), $\lambda(\mu)$, from probability expression:

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{B}}, \hat{\hat{a}}_i)}{L(\hat{\mu}, \hat{B}, \hat{a}_i)}$$

- Where μ is signal being tested (# signal events), $\hat{\hat{B}}$ is the background and $\hat{\hat{a}}_i$ background parameters that maximise S (conditional Maximum Likelihood Estimators (MLEs))
- Denominator gives best fit of data: unconstrained MLEs

Invariant Mass Resolution

$$\left(\frac{\delta_m}{m}\right)^2 = \left(\frac{\delta_p}{p}\right)^2 + 0.5 \times \left(\frac{\delta_\theta}{\theta}\right)^2$$

 $(\delta_{\theta})^2 = (\delta_{\theta_{MRE}})^2 + (\delta_{\theta_{ME}})^2$

 $\delta_p = 1 * 10^{-4} \Rightarrow \delta_\theta$ dominates

 $\delta \theta_{HRS}$ is the HRS angular resolution contribution

 $\delta \theta_{MS}$ is the Multiple Scattering contribution

• $\delta \theta_{MS}$ reduced by narrow targets (segmented):



• $(\delta_{\theta_{HRS}})$ is comprised of errors in track measurement in HRS and imperfections in optics reconstruction matrix.

Invariant Mass Resolution Function

- Need to obtain δ m as function of m: $\delta m = f(m)$
- Use angular resolutions (with multiple scattering) and momentum resolution to vary angles and momentum and calculate new mass (m'), take difference with original mass, m
- 5th order fit determined to be optimal to describe δm



APEX Peak Search: Discovery

$$\lambda(\mu=0)=rac{L(\mu=0,\hat{\hat{B}},\hat{\hat{a}_i})}{L(\hat{\mu},\hat{B},\hat{a}_i)}$$



• (Plot from J. Beacham, with $S = \mu$)

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- LEE: tested range of equally likely $m_{A'}$ hypothesis, so should punish CL (the more $m_{A'}$ hypotheses tested the more likely one is true by chance)
- crude version of correction to p values:

 $p \Rightarrow p \frac{\text{mass range}}{\text{mass res}}$

$$\epsilon^{2} = \left(\frac{\alpha'}{\alpha_{fs}}\right)_{max} = \frac{1}{f} \frac{\mu_{up}}{(B/\delta m)} \frac{2N_{eff}\alpha}{3\pi m_{A'}}$$

- $B/\delta m$ is the number of background events within a 1 MeV window around the tested mass.
- $\mu_{\rm up}$ is the upper limit on the number of signal events, as defined by the confidence level.
- N_{eff} is a scaling factor dependent on the mass of the A':

$$N_{Eff} = egin{cases} 1 & m_{A'} < 2m_{\mu} \ 2 + R(m_{A'}) & m_{A'} \geq 2m_{\mu} \end{cases}$$

where $R(m_{A'}) = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ is an energy-dependent term.